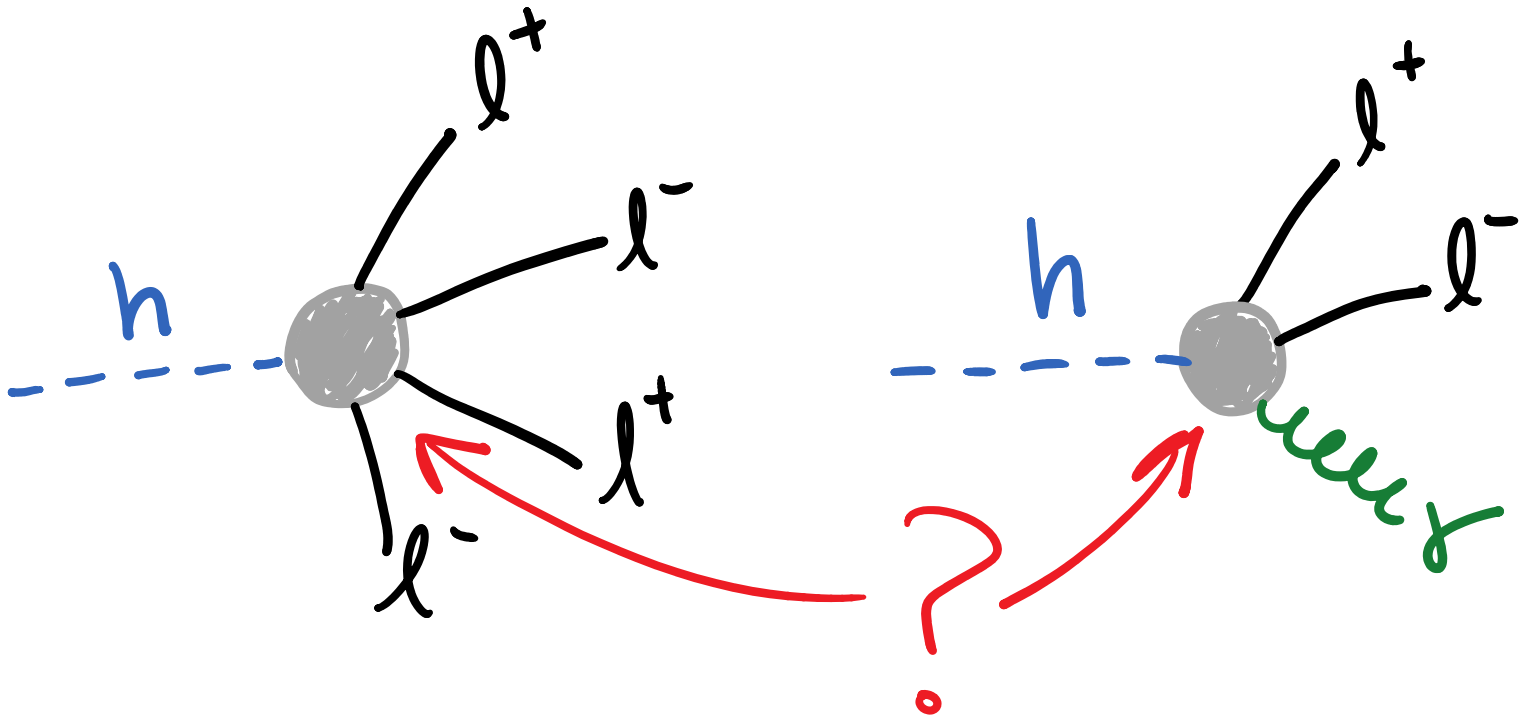
Effective Higgs couplings and CP properties in the Golden channel(s)



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COVID-HEFT 2020, University of Granada

Quarantine, Granada Spain, April 16, 2020

In collaboration with many...

Many studies of $h \to 4\ell$ and $h \to 2\ell\gamma$ decays before and after discovery...

R. M. Godbole, D. Miller, M. Muhlleitner: **0708.0458**
Q. Cao, C. Jackson, W.Y. Keung, I. Low: **0911.3398**
Y. Gao, A. V. Gritsan, Z. Guo, K. Melnikov, M. Schulze, et. al: **1001.3396**
A. De Rujula, J. Lykken, M. Pierini, C. Rogan, M. Spiropulu: **1001.5300**
S. Bolognesi, Y. Gao, A. V. Gritsan, K. Melnikov, et. al: **1208.4018**
R. Boughezal, T. LeCompte, F. Petriello: **1208.4311**
Avery, Bourilkov, Chen, Cheng, Drozdetskiy, et. al: **1210.0896**
J.M. Cambell, W.T. Giele, C. Williams: **1204.4424**
J. Gainer, J. Lykken, et. al.: **1304.4936**
P. Artoisenet, P. de Aquino, F. Demartin, F. Maltoni, et. al: **1306.6464**
Sun, Yi and Wang, Xian-Fu and Gao, Dao-Neng: **1309.4171**
Anderson, S. Bolognesi, F. Caola, Y. Gao, A. V. Gritsan, et al.: **1309.4819**
T. Chen, J. Gainer, et. al.: **1310.1397**
Gonzales-Alonso, Isidori: **1403.2648**
J. Gainer, J. Lykken, K. T. Matchev, S. Mrenna, M. Park: **1403.4951**
M. Beneke, D. Boito, Y. Wang: **1406.1361**
M. Gonzalez-Alonso, A. Greljo, G. Isidori, and D. Marzocca: **1504.04018**
M. Bordone, A. Greljo, G. Isidori, D. Marzocca, A. Pattori: **1507.02555**
J. S. Gainer, M. Gonzalez-Alonso, et. al. **1808.00965**
A. V. Gritsan, J. Roskes, et. al. **2002.09888**
+ **many others** as well as **various ATLAS and CMS studies**

Physics Possibilities in $h \to 4\ell$ and $h \to 2\ell\gamma$

- Probing Higgs CP properties

  (Y. Chen, R. Harnik, RVM: 1404.1336, 1503.05855)
- New Observables for CP violation in Higgs decays

  (Y. Chen, A. Falkowski, I. Low, RVM: 1405.6723)
- Extracting effective Higgs hVV couplings

  (Y. Chen, N. Tran, RVM: 1211.1959, 1310.2893)
- Hypothesis testing & multi-parameter extraction at LHC

  (Y. Chen, RVM + others: 1108.2274, 1208.4840, 1401.2077, 1410.4817, 1411.3441)
- Exotic Higgs decays

  (A. Falkowski, RVM: arXiv:1404.1095)
- Probing top Yukawa CP properties

  (Y. Chen, D. Stolarski, RVM: 1505:01168)
- Testing Custodial symmetry

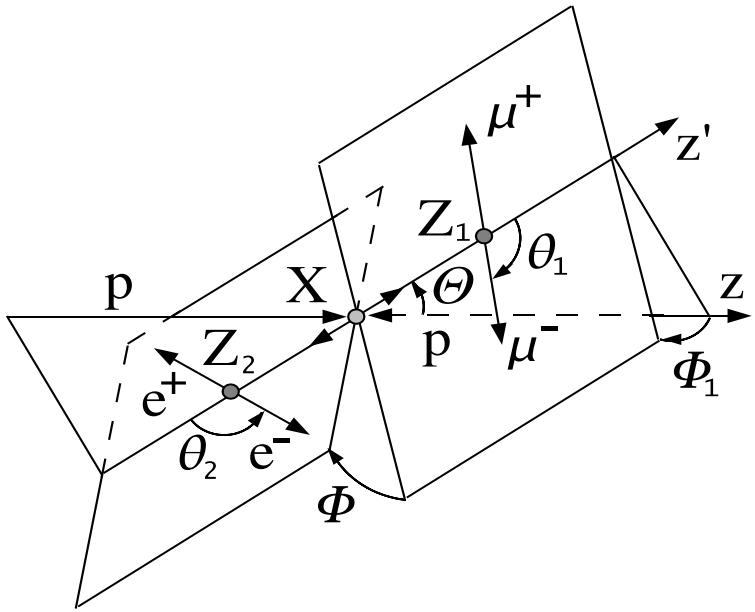
  (Y. Chen, J. Lykken, M. Spiropulu D. Stolarski, RVM: 1608:02159)
- Probing non-linear Higgs dynamics

  (D. Liu, I. Low, RVM: 1904.00026)

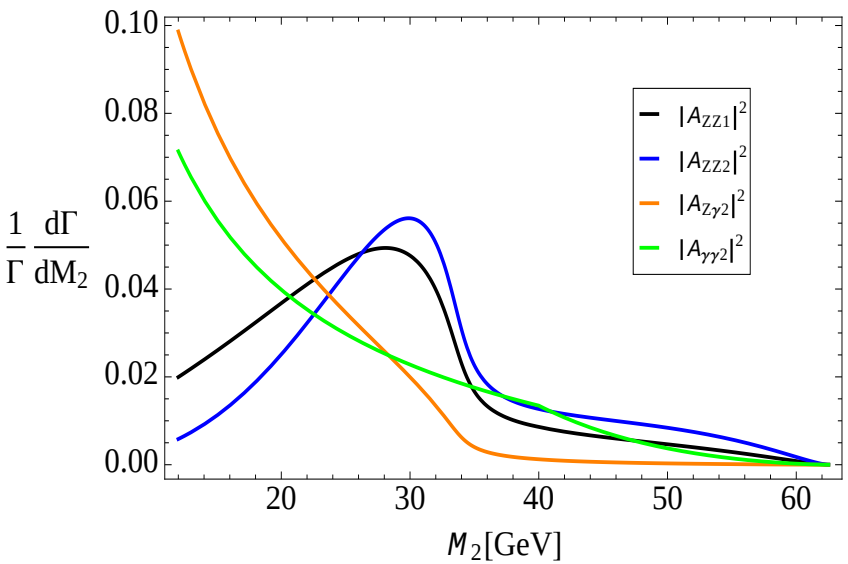
(Not exhaustive list of possibilities!)

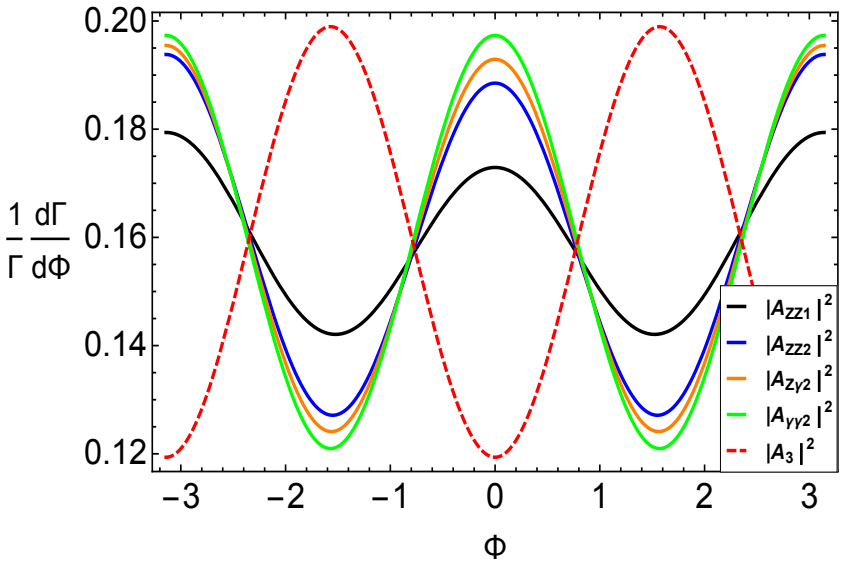
ID-ing the Higgs with Kinematic Distributions

- Sensitivity comes from the many kinematic observables and their correlations
- They contain information about CP properties and tensor structure of the Higgs



(Y. Chen, R. Harnik, RVM: 1404.1336)



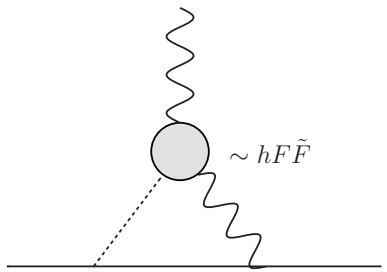


Searching for CP Violation in hVV Couplings

- 'Smoking gun' of BSM physics which could perhaps be connected with baryogenesis $\Rrightarrow$ matter/anti-matter asymmetry
- Many indirect constraints of CP violation:
  - Constraints from EWPD
  - Measurements of $h \to SM$ decay rates
  - The most severe come from EDMs
- These are indirect and rely on model dependent assumptions

Even here you need to close the circle, since EDM constraints assume 1st gen Higgs couplings that you can't measure

γ operator:
already severely constrained
by e and q EDMs
McKeen, Pospelov, Ritz '12



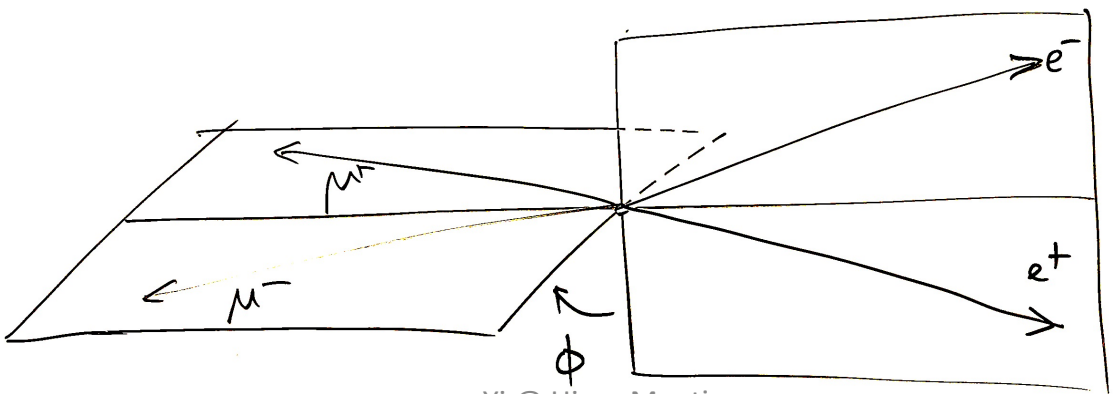
(see also V. Cirigliano, A. Crivellin, et.al.: 1903.03625)

- We would like direct probes of CP free of these assumptions

'Conventional' CP Violation via Triple Products

- Typically rely on constructing a CP-odd triple product asymmetry
- Need four visible 4-momenta to construct CPV observable
- One example is the azimuthal angle between decay planes of a four-body Higgs decay such as in $h \to 4\ell$

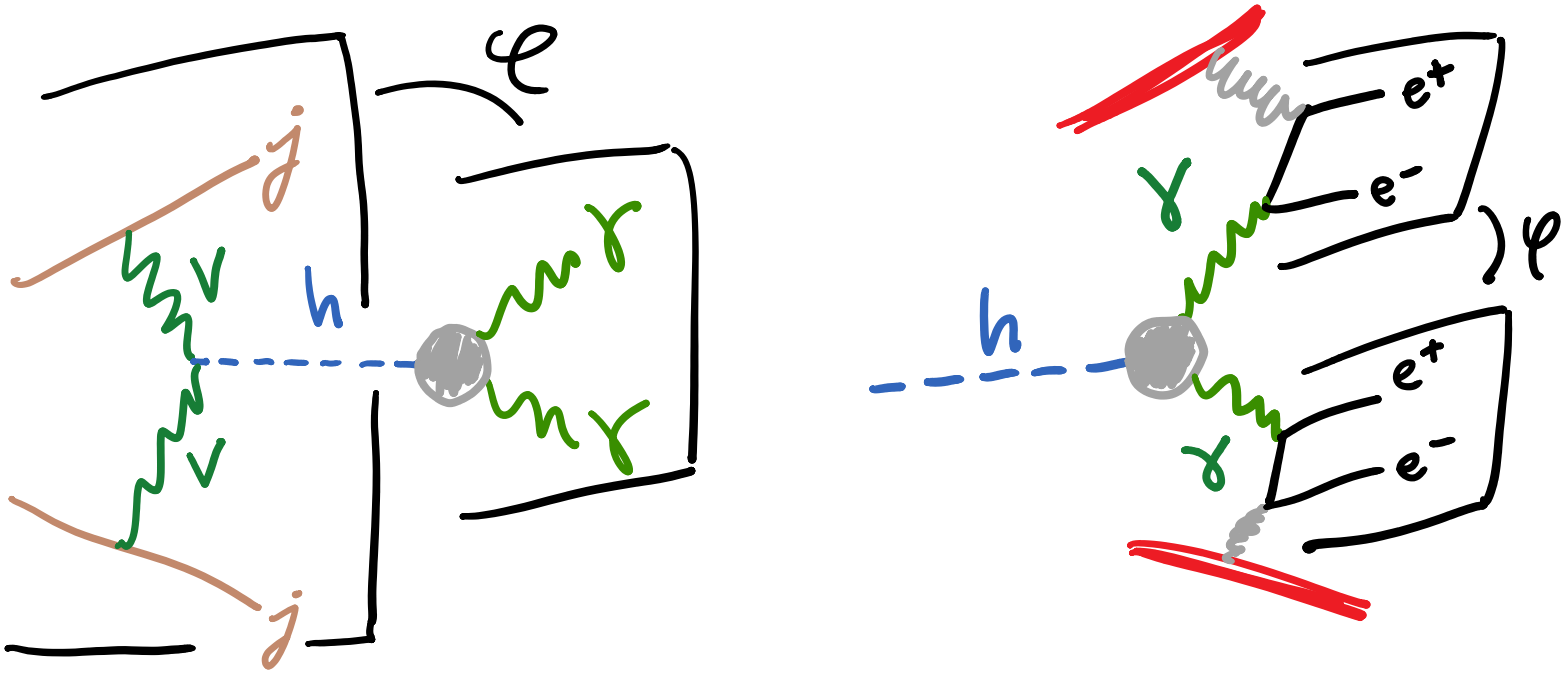
$$\cos\phi = \frac{(\vec{p}_1 \times \vec{p}_2) \cdot (\vec{p}_3 \times \vec{p}_4)}{|\vec{p}_1 \times \vec{p}_2| \; |\vec{p}_3 \times \vec{p}_4|}$$



- For this type of CPV only need distinct 'weak phases' (phases that change sign under CP) in amplitudes which are interfering

Proposals for Direct Probes of $h\gamma\gamma$ CP Properties

- Can we directly probe the CP nature of $h - \gamma\gamma$ couplings?
- Various proposals which include:
  - Measuring correlations in $VBF \to \gamma\gamma$ (M. Buckley, M. Ramsey-Musolf: 1208.4840)
  - Measuring correlations between photons which convert in detector (F. Bishara, Y. Grossman, R. Harnik, D. Robinson, J.Shu, J. Zupan: 1312.2955)

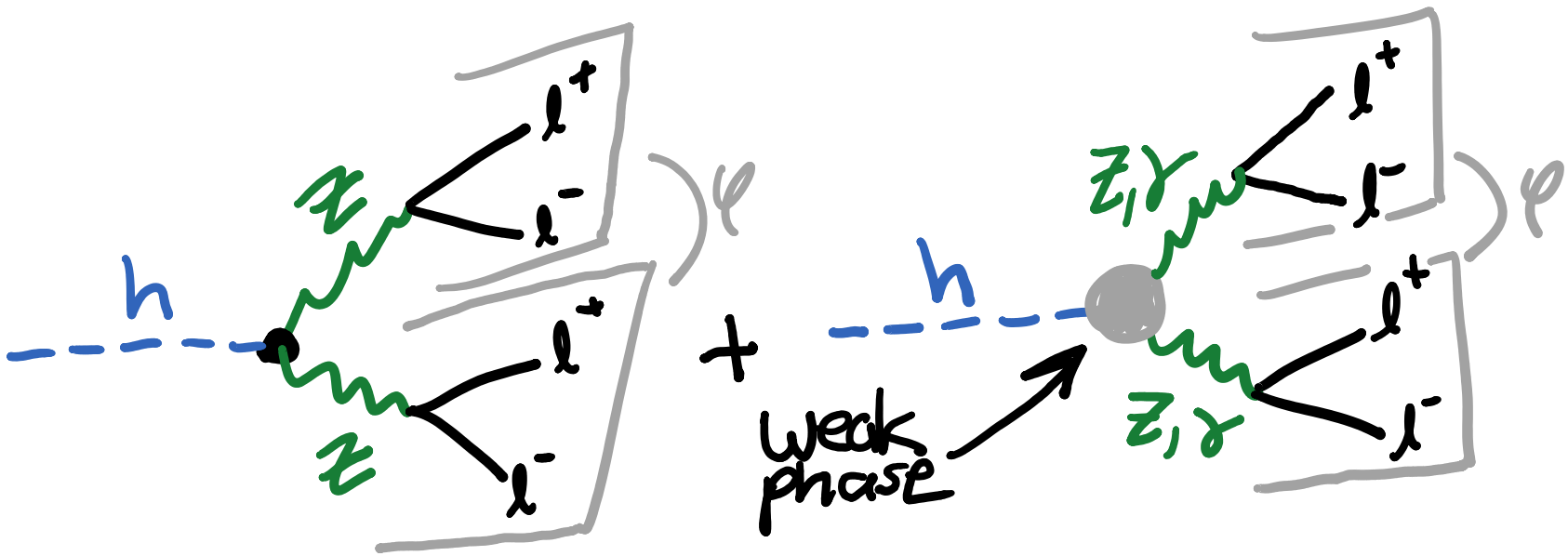


- Interesting possibilities...experimentally challenging measurements

Probing CPV in hZZ and $hV\gamma$ with $h \to 4\ell$

- Sensitivity is driven by interference between tree level ZZ mediated amplitude and higher order $VV = ZZ, Z\gamma, \gamma\gamma$ mediated decays

  (Y. Chen, RVM: 1310.2893, Y. Chen, R. Harnick, RVM: 1404.1336, 1503.05855)



- The effective couplings to VV provide the potential weak phases
- BUT...CPV observables also possible without 4 visible momenta!

CP Violation Without Triple Products

- Consider decay into CP conjugate final states F and $\bar{F}$
- Conditions necessary for CPV without triple products:
  - Interference between different amplitudes

$$\mathcal{M}_F = \mathcal{M}_1 + \mathcal{M}_2$$

  - Distinct strong and weak phases for $\mathcal{M}_1$ and $\mathcal{M}_2$

$$\mathcal{M}_i = |c_i| e^{i(\delta_i + \phi_i)}$$

(where $\delta_i \to \delta_i$ and $\phi_i \to -\phi_i$ under CP)

  - Need a CPV observable such as an asymmetry

$$A_{\mathrm{CP}} = \frac{d\Gamma_F - d\Gamma_{\bar{F}}}{d\Gamma_F + d\Gamma_{\bar{F}}} \propto |c_1||c_2| \sin(\delta_1 - \delta_2) \sin(\phi_1 - \phi_2)$$

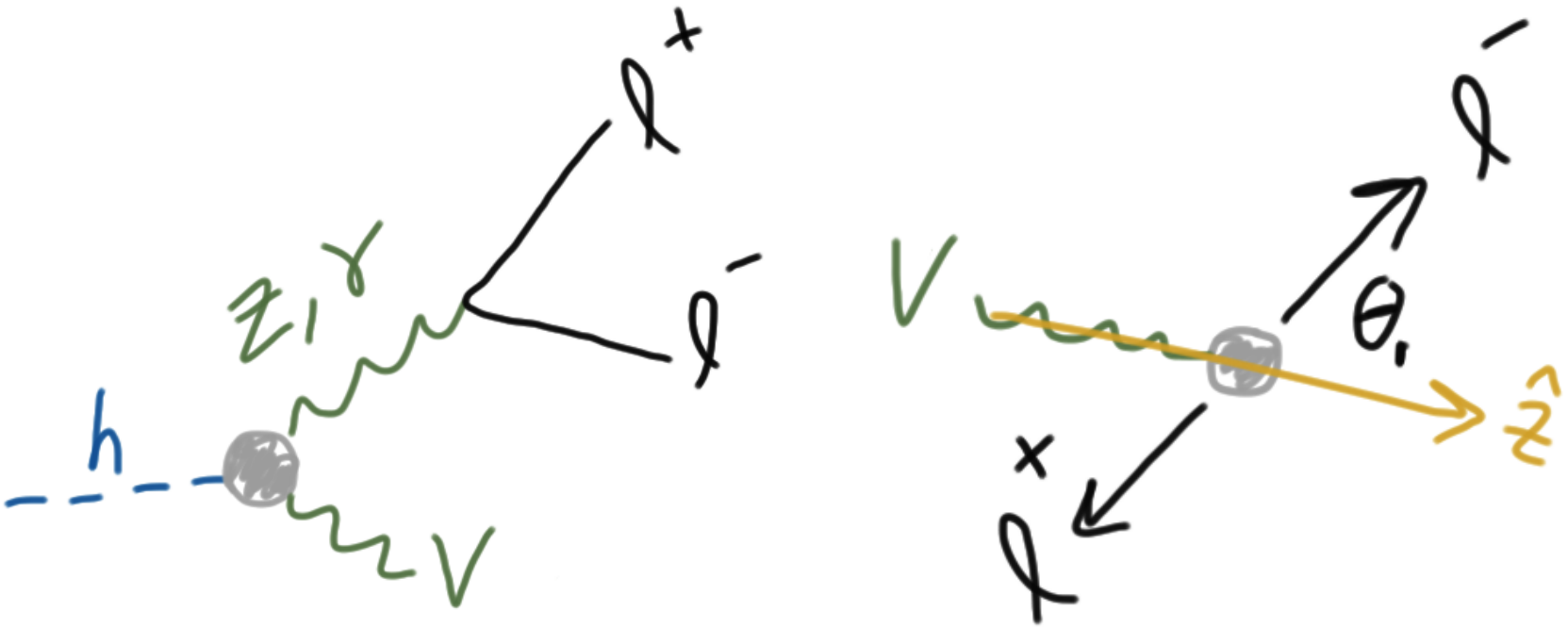
- Note that the last condition requires $\mathcal{M}_F \neq CP(\mathcal{M}_F) \equiv \mathcal{M}_{\bar{F}}$
- What kind of physics/processes can satisfy these conditions?

A well known effect in flavor physics and studied in BSM context by J. Berger, et al: 1105.0672

New Observables for CPV in Higgs Decays

(Y. Chen, A. Falkowski, I. Low, RVM: 1405.6723)

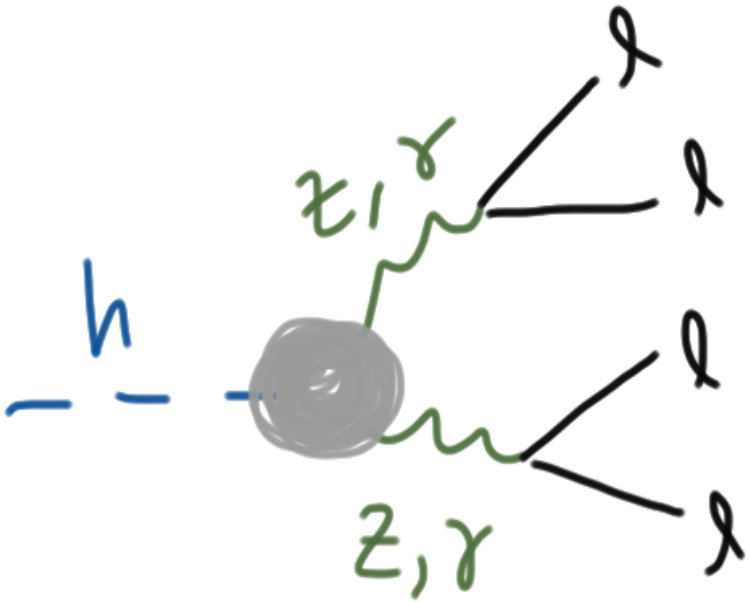
- Our primary example of this type of CPV is $h \to 2\ell V$ $(V = \gamma, Z)$
- Observable as an asymmetry in polar angle of final state lepton ℓ^-



- Generally an asymmetry $\neq$ CPV (e.g. $e^+e^- \to f\bar{f}, WW$ @ LEP)
- Can also utilize interference with BG (for gluon fusion production)

  (see M. Farina, Y. Grossman, D. J. Robinson: 1503.06470, X. Chen, G. Li, X. Wan: 1705.01254)
- HL-LHC may have a chance to observe this asymmetry

Effective Higgs Couplings at the LHC



- We consider $h \to VV \to 4\ell$ where $4\ell \equiv 2e2\mu, 4e, 4\mu$ and $VV = ZZ, Z\gamma, \gamma\gamma$
- Can parametrize the hVV couplings with an effective Lagrangian (up to D = 5)

$$\mathscr{L} = \frac{h}{4v}\Big(2m_Z^2 A_1^{ZZ} Z_\mu Z^\mu$$

Background

$$+ A_2^{ZZ} Z_{\mu\nu} Z^{\mu\nu} + A_3^{ZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu}$$

Signal

$$+ A_2^{\gamma\gamma} F_{\mu\nu} F^{\mu\nu} + A_3^{\gamma\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

$$+ 2A_2^{Z\gamma} Z_{\mu\nu} F^{\mu\nu} + 2A_3^{Z\gamma} Z_{\mu\nu} \tilde{F}^{\mu\nu}\Big)$$

Constructing a Likelihood Analysis Framework

- A likelihood can be formed out of probability density functions (*pdfs*) using some set of observables as follows

$$L(\vec{A}) = \prod_{\mathcal{O}}^{N} \mathcal{P}(\mathcal{O}|\vec{A})$$

(where $\mathcal{O}$ is set of observables and $\vec{A}$ a set of undetermined parameters)

- For $pp \to h \to 4\ell$ we construct the pdf from the differential cxn:

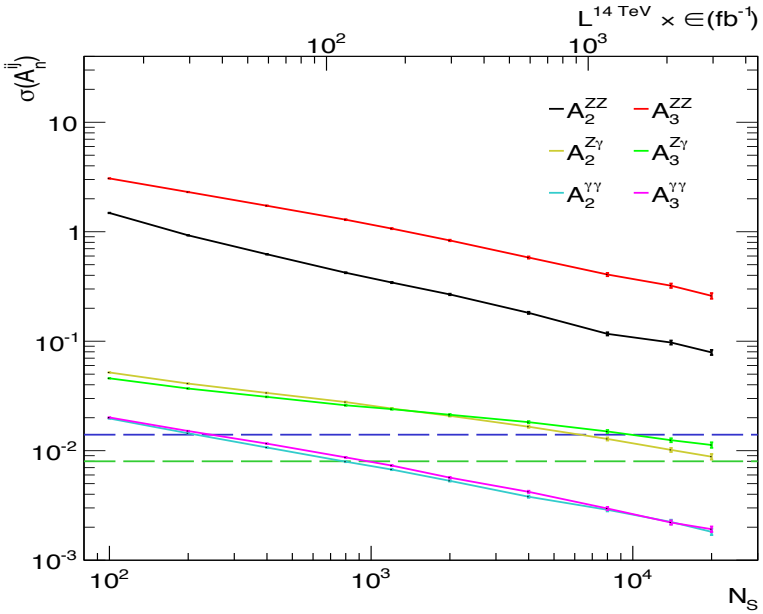
$$P(\vec{p}_T, Y, \phi, \hat{s}, M_1, M_2, \vec{\Omega}|\vec{A}) =$$

$$W_{\text{prod}}(\vec{p}_T, Y, \phi, \hat{s}) \times \frac{d\sigma_{4\ell}(\hat{s}, M_1, M_2, \vec{\Omega}|\vec{A})}{dM_1^2 dM_2^2 d\vec{\Omega}}$$

- Construct ratios $\Lambda = L(A_a)/L(A_b) \Rightarrow$ hypothesis testing
- Perform parameter extraction via maximization of the likelihood

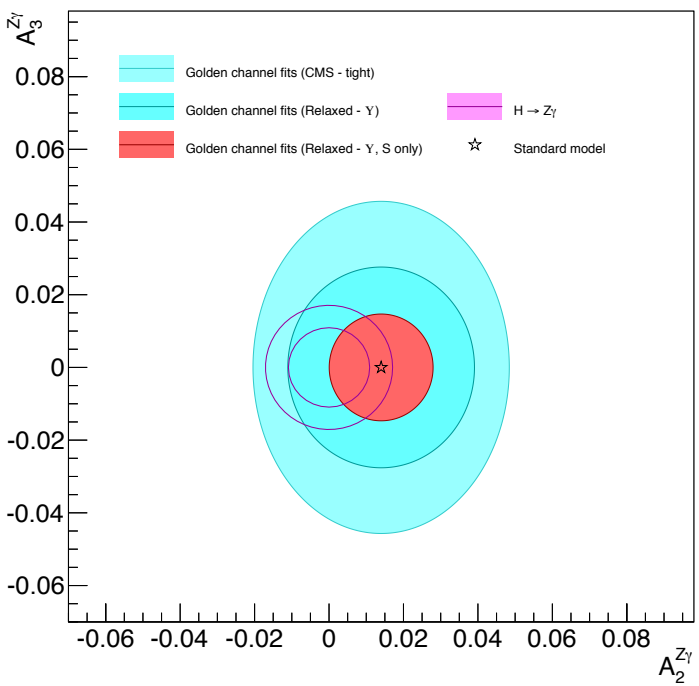
$$\frac{\partial L(\vec{A})}{\partial \vec{A}}\Big|_{\vec{A}=\hat{A}} = 0$$

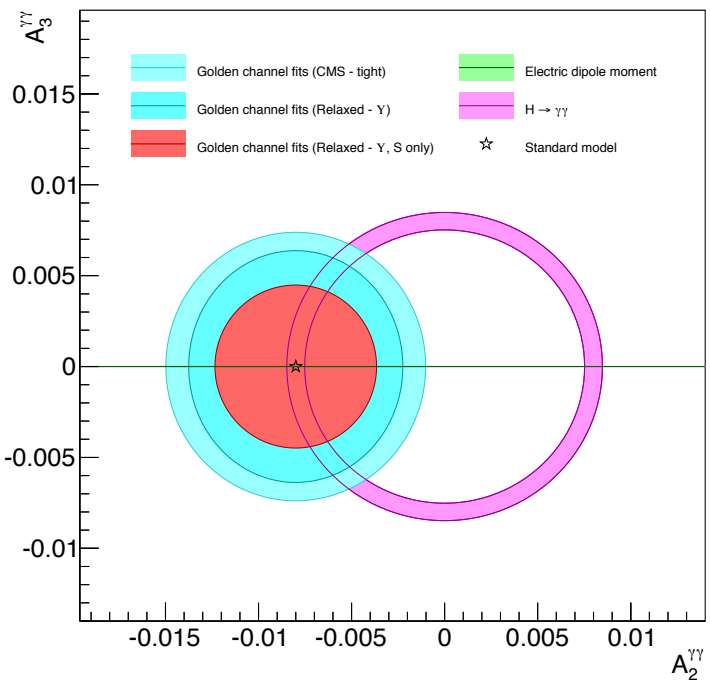
Probing Effective Couplings at the LHC



(Y. Chen, R. Harnik, RVM: 1503.05855)

- Perform 6D fit to $ZZ, Z\gamma, \gamma\gamma$ 'anomalous' Higgs couplings
- Stronger sensitivity to $Z\gamma$ and $\gamma\gamma$ effective couplings
- Can probe $Z\gamma$ and $\gamma\gamma$ CP properties at HL-LHC





'Detector level' Likelihood

- Of course what we really want is to do all of this at 'detector level'
- Need a likelihood that takes *reconstructed* observables as input
- Can be done via convolution of *analytic* 'generator level' *pdf* with a transfer function $T(\vec{X}^R|\vec{X}^G)$ over generator level observables

$$P(\vec{X}^{\mathrm{R}}|\vec{A}) = \int P(\vec{X}^{\mathrm{G}}|\vec{A})T(\vec{X}^R|\vec{X}^G)d\vec{X}^{\mathrm{G}}$$

$$\vec{X} \equiv (\vec{p}_T, Y, \phi, \hat{s}, M_1, M_2, \vec{\Omega})$$

Note: Not done by MC integration ⇒ COV and numerical techniques

- This integration takes us from generator level observables ($\vec{X}^G$) to detector level (reconstructed) observables ($\vec{X}^R$)

(details can be found in 1401.2077 and technical note 1410.4817)

- $T(\vec{X}^R|\vec{X}^G)$ represents probability to observe $\vec{X}^R$ given $\vec{X}^G$
- Can be optimized for specific detector and included in convolution

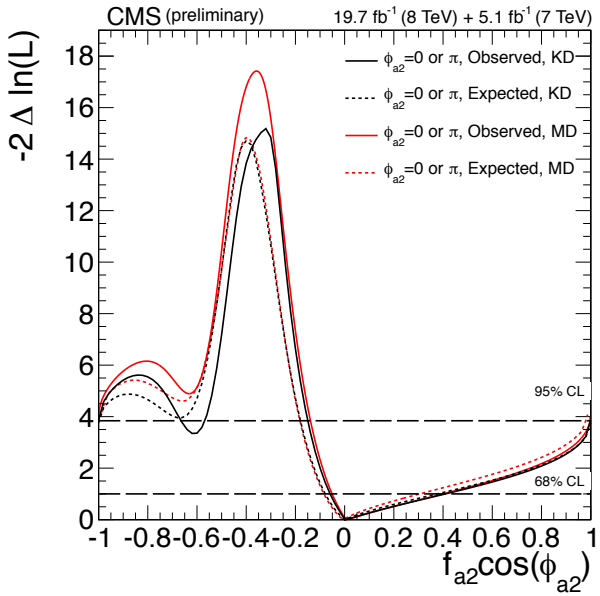
Likelihood Framework in CMS Analysis

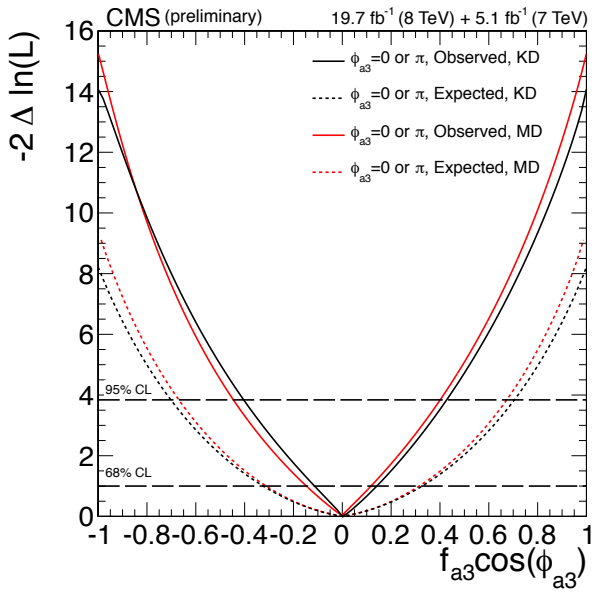
CMS PAS HIG-14-014, arXiv: 1411.3441

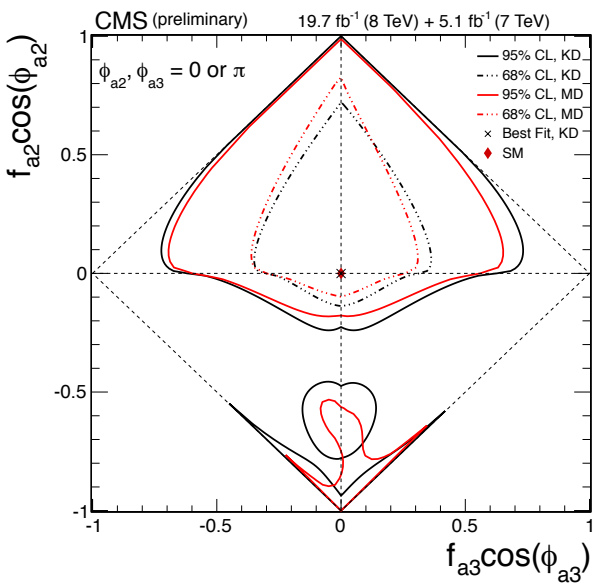
- A multi-dimensional Higgs couplings extraction framework

  Y. Chen, N. Tran, RVM: arXiv:1211.1959, Y. Chen, RVM: arXiv:1310.2893,
  Y. Chen, E. DiMarco, J. Lykken, M. Spiropulu, RVM, S. Xie: arXiv:1401.2077, arXiv:1410.4817

- Used in 2014 CMS study of anomalous hVV couplings in $h \to 4\ell$





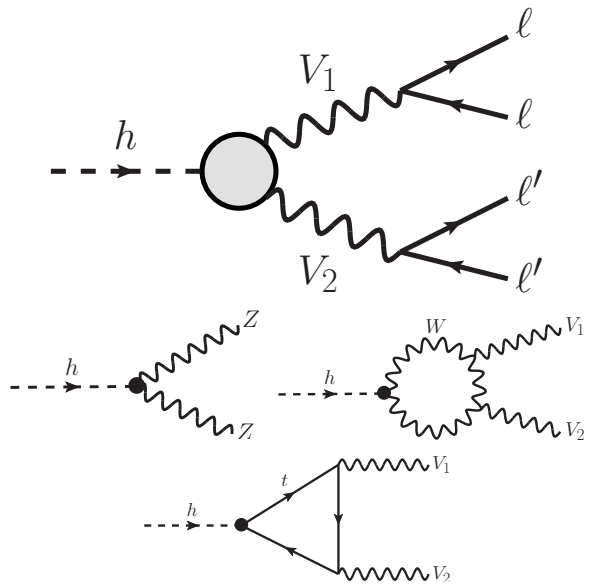


- Used in a limited scope and validated with other frameworks
- Can utilize full power of framework in future LHC studies

IF TIME PERMITS!

Loop effects in Higgs to four lepton decays

- Various loop effects can enter in hVV couplings
- Dominated by tree level hZZ mediated amplitude



- Can study the nature of top and W couplings to the Higgs

$$\mathcal{L}_{ZW} \supset \frac{h}{v}\left(g_Z m_Z^2 Z^\mu Z_\mu + 2 g_W m_W^2 W^{\mu+} W^-_\mu\right).$$

$$\mathcal{L}_t \supset \frac{m_t}{v} h\bar{t}(y_t + i\tilde{y}_t\gamma^5)t$$

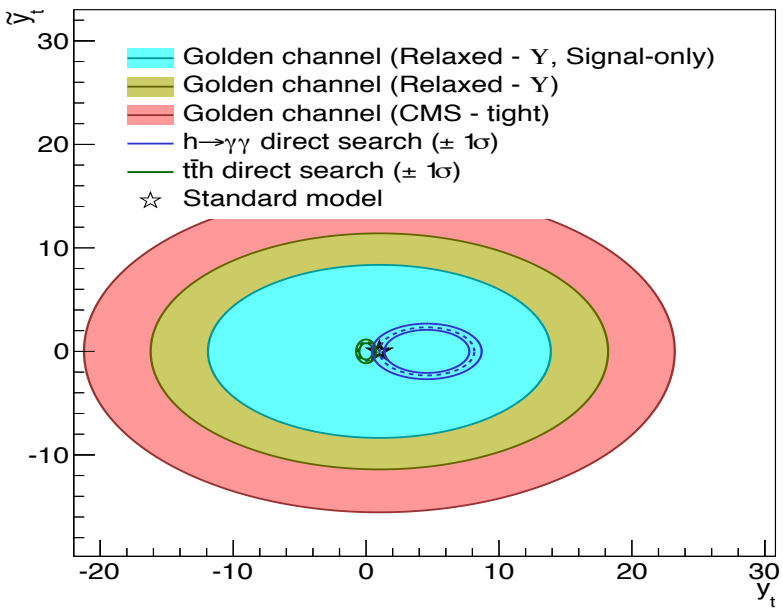
- Interference between tree level hZZ amplitude and loop diagrams allows us to probe CP properties and phases

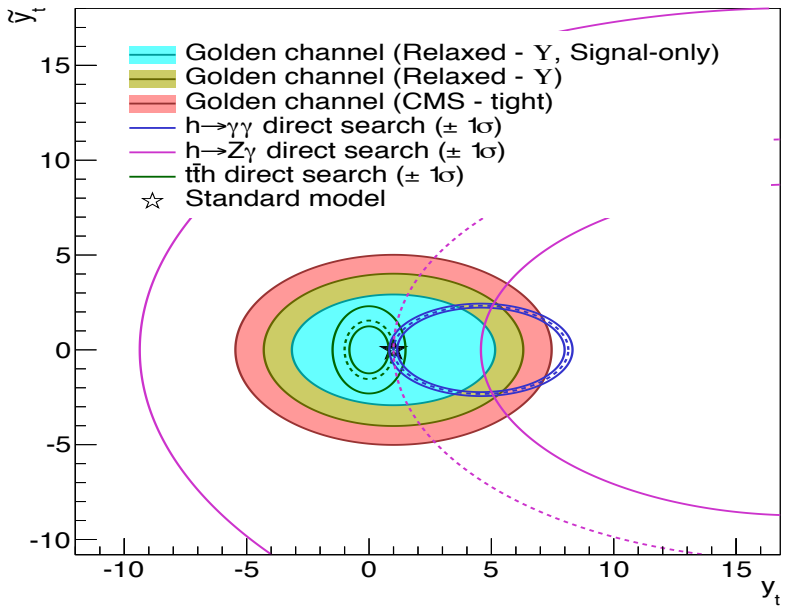
Probing Top Yukawa CP Properties in $h \to 4\ell$

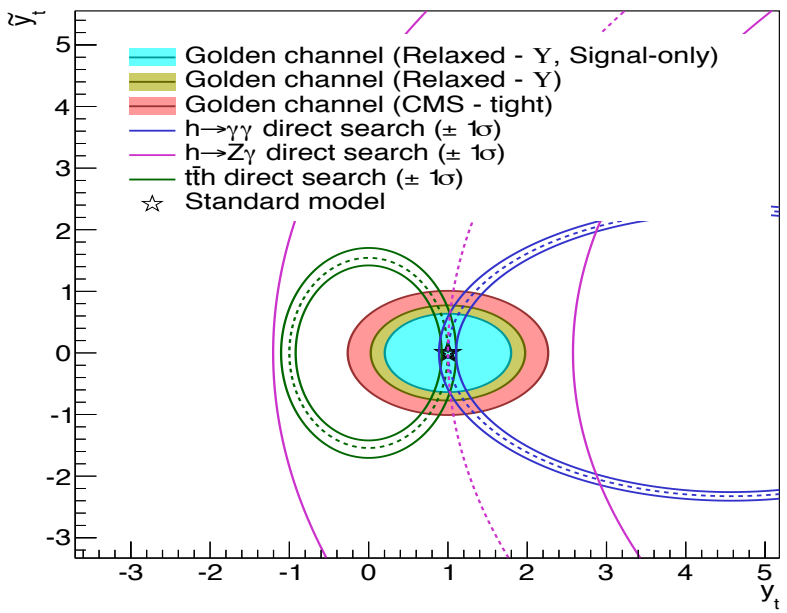
(Y. Chen, D. Stolarski, RVM: 1505:01168)

- Compare with other probes such as $h \to \gamma\gamma$, $h \to Z\gamma$, and tth
- Qualitatively different probe of the top Yukawa CP properties

(Y. Chen, D. Stolarski, RVM: 1505.01168)







- Not yet sensitive, but should become at high luminosity LHC

The Custodial Nature of the Higgs Boson

- Custodial symmetry ($\rho_{\text{tree}} = 1$) restricts possible values of $\lambda_{WZ} = g_W/g_Z$ to two possibilities (I. Low, J. Lykken, arXiv: 1005.0872):

$$\lambda_{WZ} = +1 \ \ (\text{custodial singlet})$$
$$\lambda_{WZ} = -1/2 \ \ (\text{custodial fiveplet})$$

- Custodial fiveplet can be found in custodial Higgs triplet models

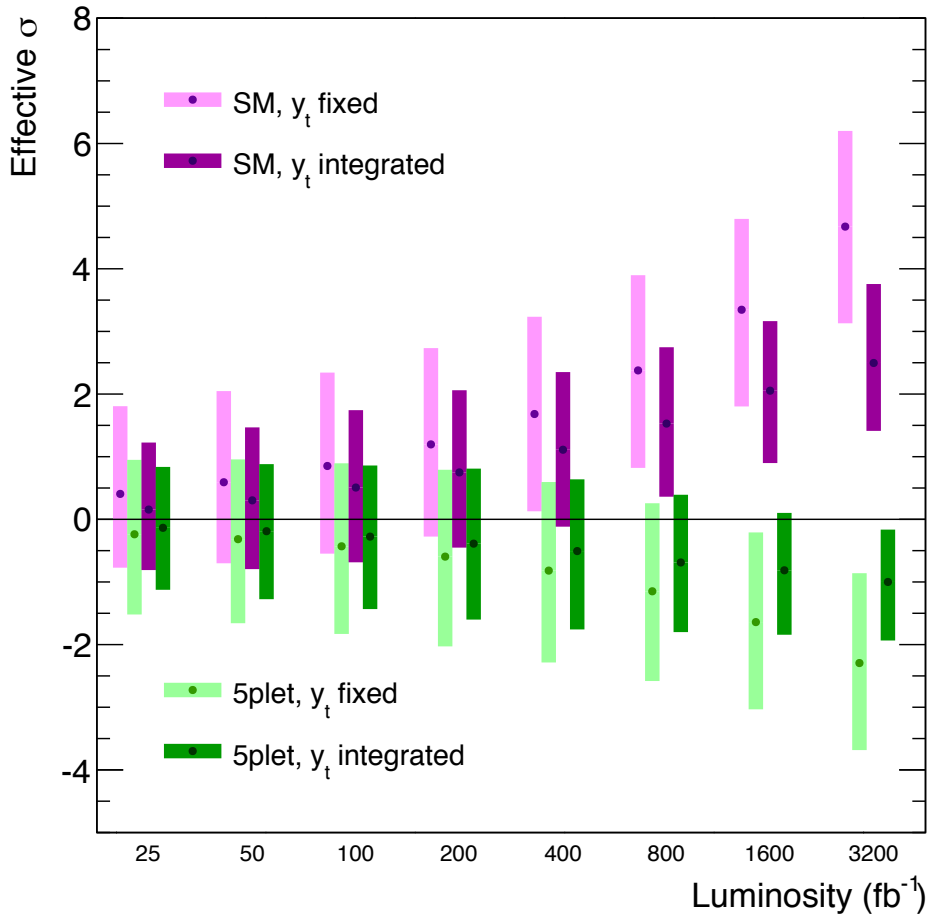
  (H. Georgi and M. Machacek (1985), S. Gori, M. Quiros, RVM, et.al., arXiv: 1308.4025, 1409.5737)

- Custodialy violating effects occur at NLO, but too small to generate $\mathcal{O}(1)$ corrections needed to change overall sign
- Thus simply establishing the sign effectively tells us the custodial representation of the Higgs boson

Pinning the Sign Down of λ_{WZ} at the LHC

(Y. Chen, D. Stolarski, RVM, J. Lykken, M. Spiropulu 1608.02159)

- Can establish sign of λ_{WZ} independently of top Yukawa

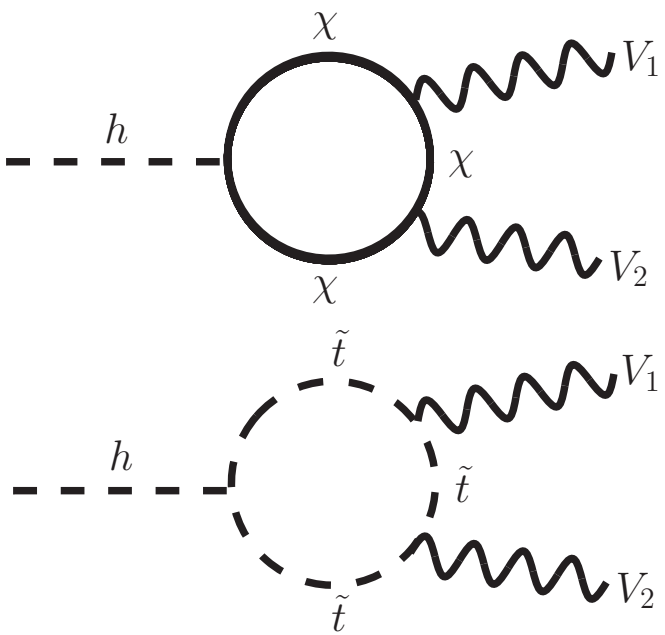


- Does not rely on other measurements of Higgs couplings
- Rate information not used, largely independent of production

Searching for SUSY in hVV Loops (ongoing)

(Y. Chen, P. Smith, D. Stolarski, RVM: in progress)

- SUSY particles can enter in these loops
- Can search for effects of light squarks, sleptons, charginos, neutralinos, or exotic Higgs bosons



- Studying sensitivity at the LHC and beyond

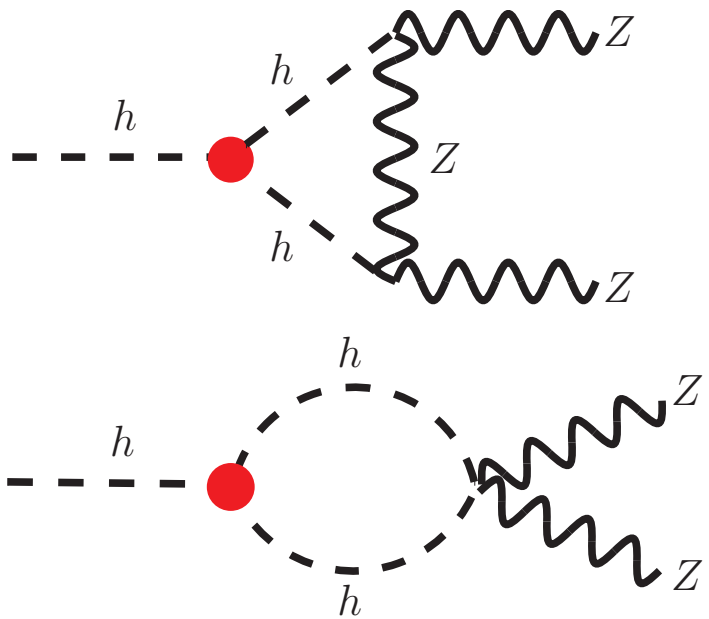
Probing the Higgs Quartic Coupling (ongoing)

(Y. Chen, P. Smith, D. Stolarski, RVM: in progress)

- Indirect probes such as $gg \to h$ and $h \to \gamma\gamma$ competitive with 'direct' di Higgs searches

  (M. Gorbahn, U. Haisch:: 1607.03773, G. Degrassi, P. P. Giardino, F. Maltoni, D. Pagani: 1607.04251)

- In $h \to 4\ell$ quartic coupling enters in hZZ loop



- Studying sensitivity at the LHC and beyond

Conclusions

- $h \to 4\ell$ an indispensable tool to study Higgs and search for BSM
- Can use $h \to 4\ell$ (and $h \to 2\ell\gamma$) to study effective Higgs couplings to $ZZ, Z\gamma$, and $\gamma\gamma$ as well as underlying loop effects
- Gives a direct probe of CP properties of the Higgs boson
- $h \to 4\ell$ serves as complementary, but qualitatively different measurement to $h \to Z\gamma$ and $h \to \gamma\gamma$ two-body decays
- HL-LHC phase should begin probing many possibilities

THANKS!

(Wish you could all be here instead!)